Membrane Wing Aerodynamics for μAV Applications

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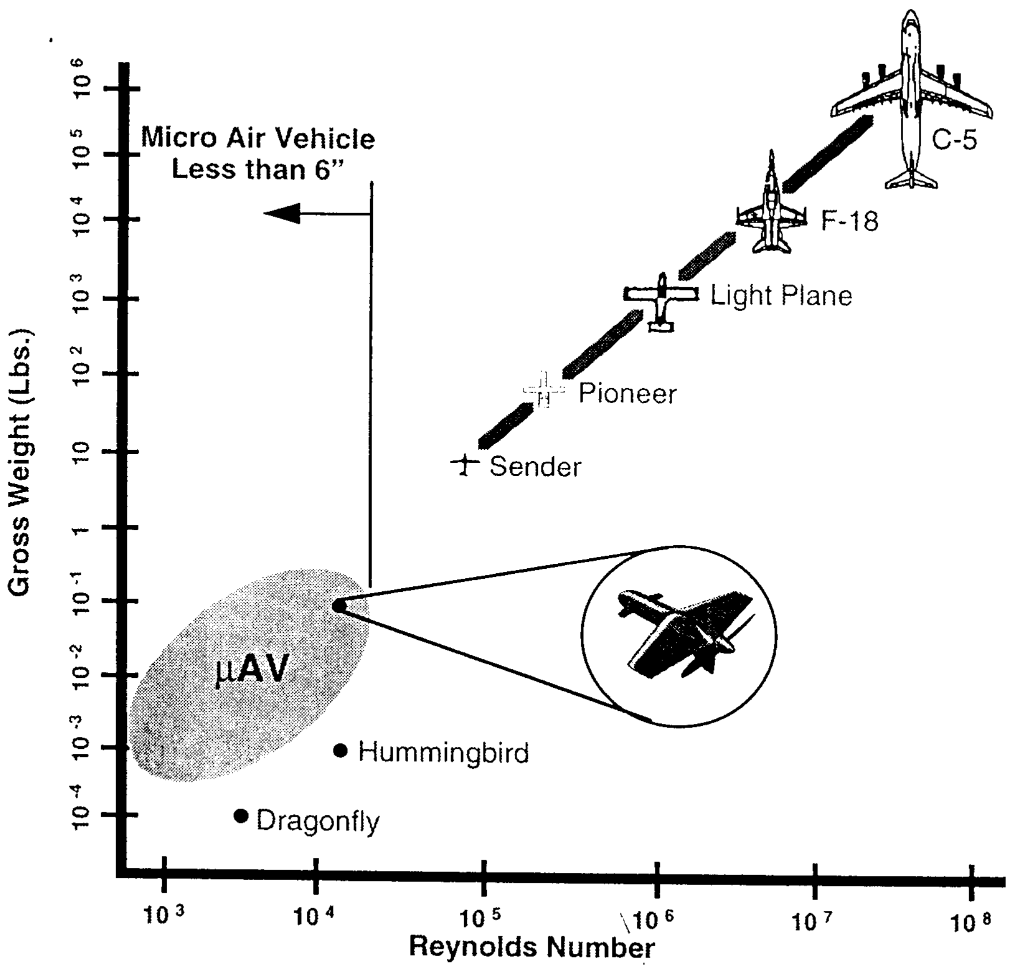
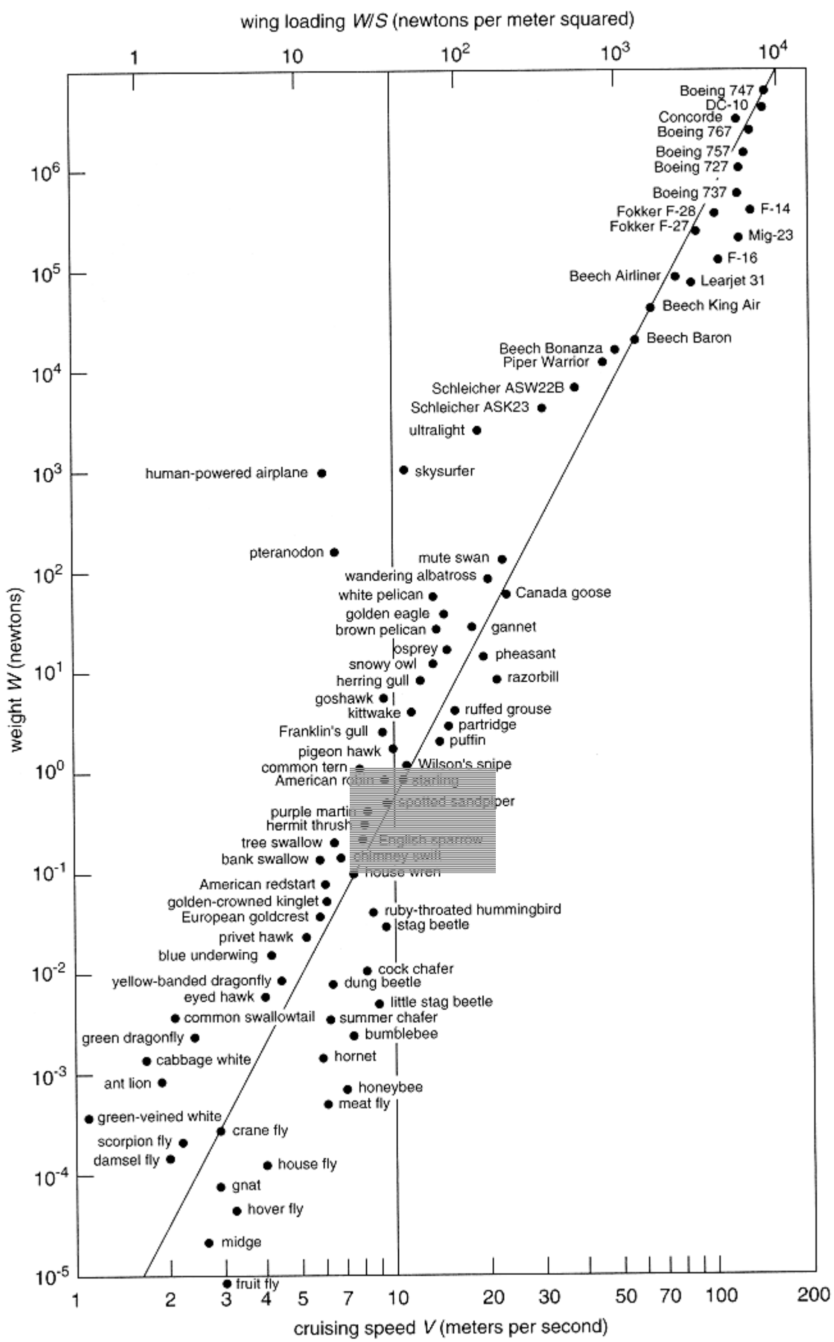
Scope of This Talk

- Overview of Univ. Florida μAV
- Summarize computational capabilities for fluid/structure interactions: membrane and surrounding viscous flow.
- Present the aerodynamics of self-excited membrane and MAV implications.
- Discuss the wing shape optimization for μAV Applications.

Characteristics of μAV



- Micro Air Vehicle (μAV) smaller than 6″, Speed 10m/s. Many applications.
- Low Reynolds number (10^4-10^5) condition: degraded L/D
- Flight environment intrinsically unsteady.



The Great Flight Diagram

(modified from Tennekes)

weight ~ l^3

wing loading ~ l

wing beat freq. ~ l^{-1}

stall speed ~ $(2W/rSC_l)$

~ $l^{0.5}$

P/W= (D/L)V ~ $l^{0.5}$

Small Birds:

*Can **fly slower**,*

*Need to **flap faster**,*

*Need **less energy density**,*

*But can **store MUCH less**,*

Can sustain

***higher impact velocity**.*

μAV: Geometric & Aerodynamic Scaling

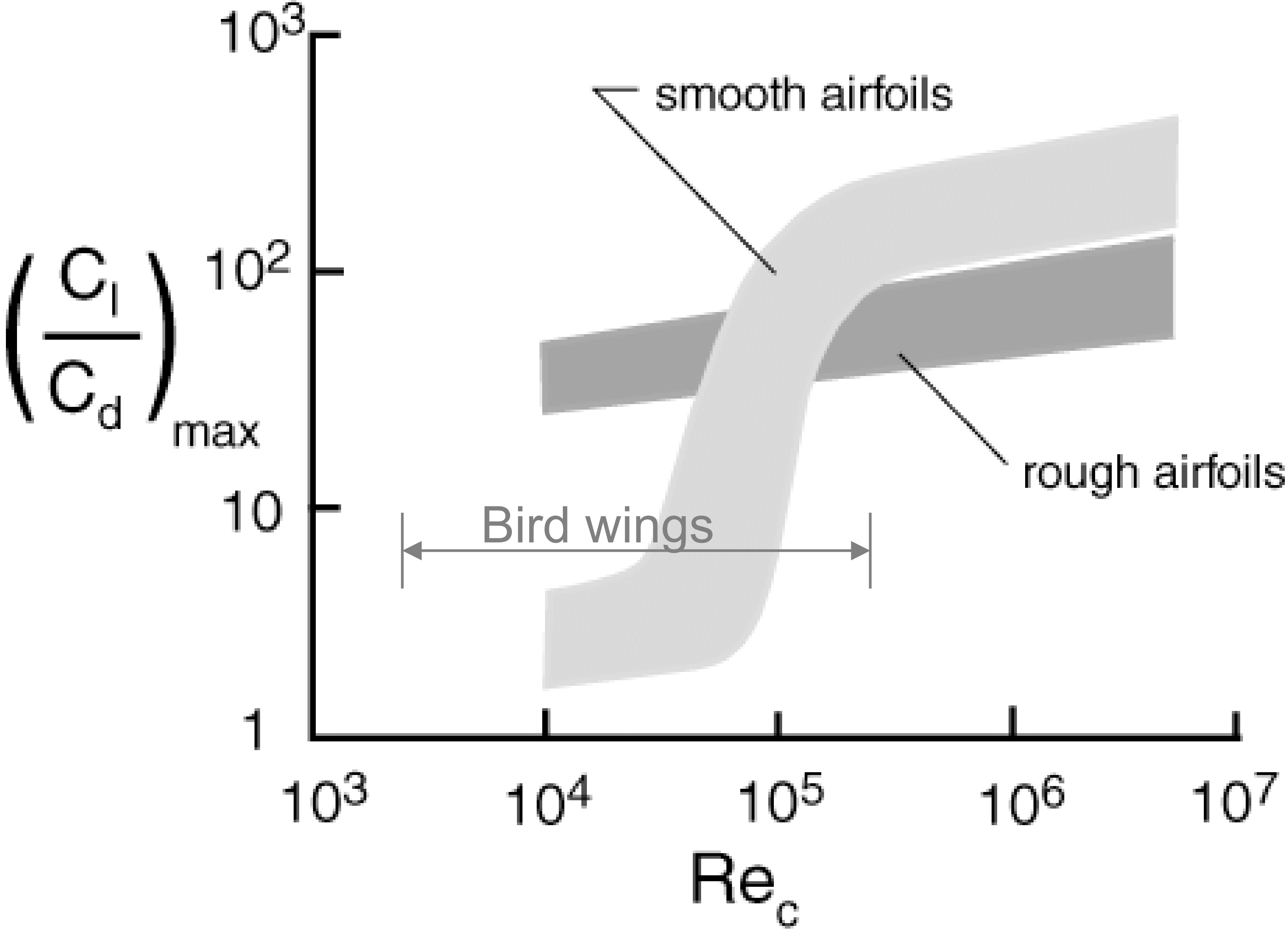
Geometric Scaling: If aerodynamics is unchanged, the power requirement decreases as the vehicle size is reduced.

Aerodynamic Scaling: Aerodynamic performance degrades as the vehicle size, and hence Re, decreases.

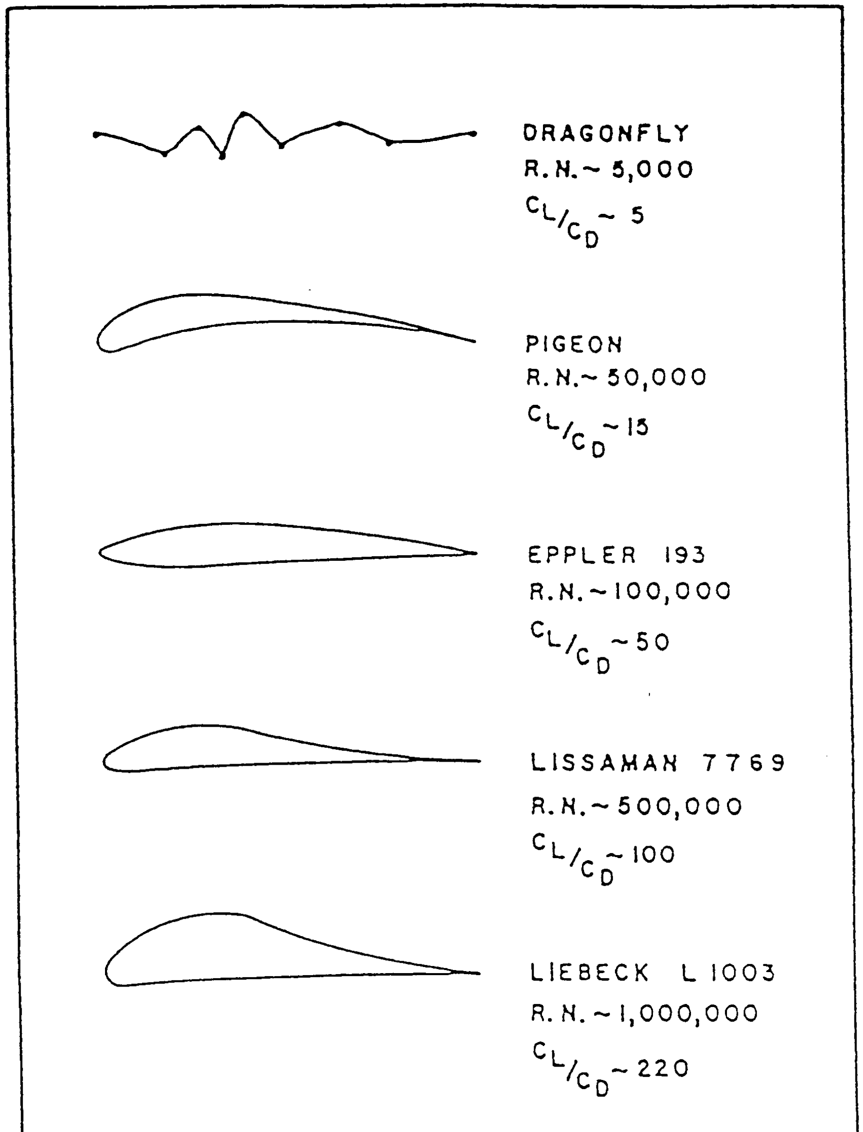
$$P = W\left(\frac{C_D}{C_L^{3/2}}\right)\sqrt{\left(\frac{2}{\rho}\right)\left(\frac{W}{S}\right)}$$

Low Reynolds Number Airfoils

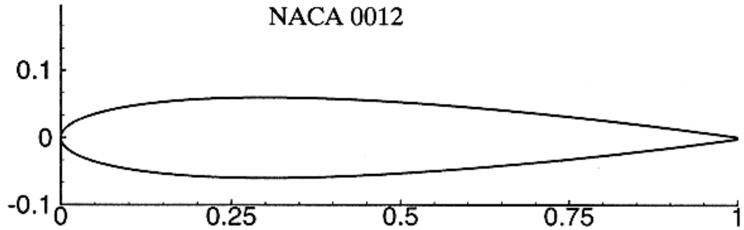
- **Gusts affect small birds and μAVs more than large ones**



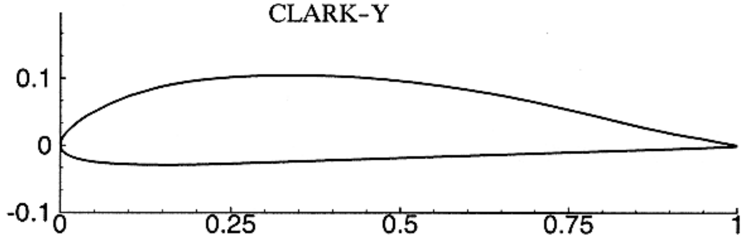
Representative Low-Reynolds-Number Airfoils (from Lissaman)



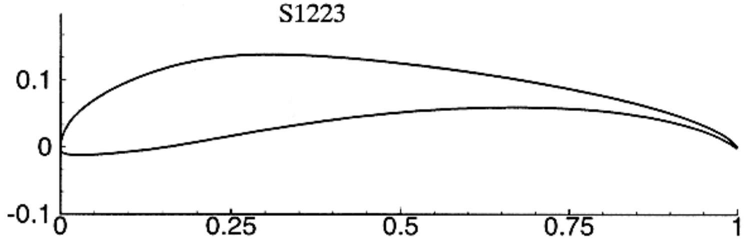
Selected Airfoil Profiles



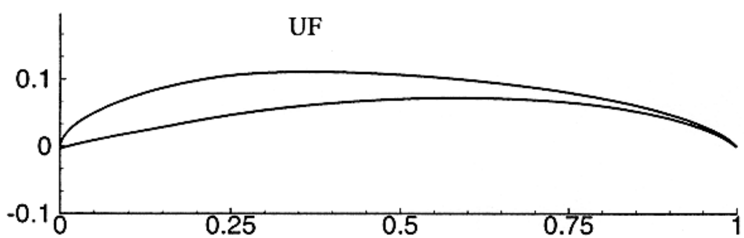
Area	0.08220
Thick.	0.12003
Camber	0.00000
Rad_{LE}	0.01527
$\Delta\theta_{TE}$	15.97°



Area	0.08700
Thick.	0.12951
Camber	0.04021
Rad_{LE}	0.01972
$\Delta\theta_{TE}$	12.88°

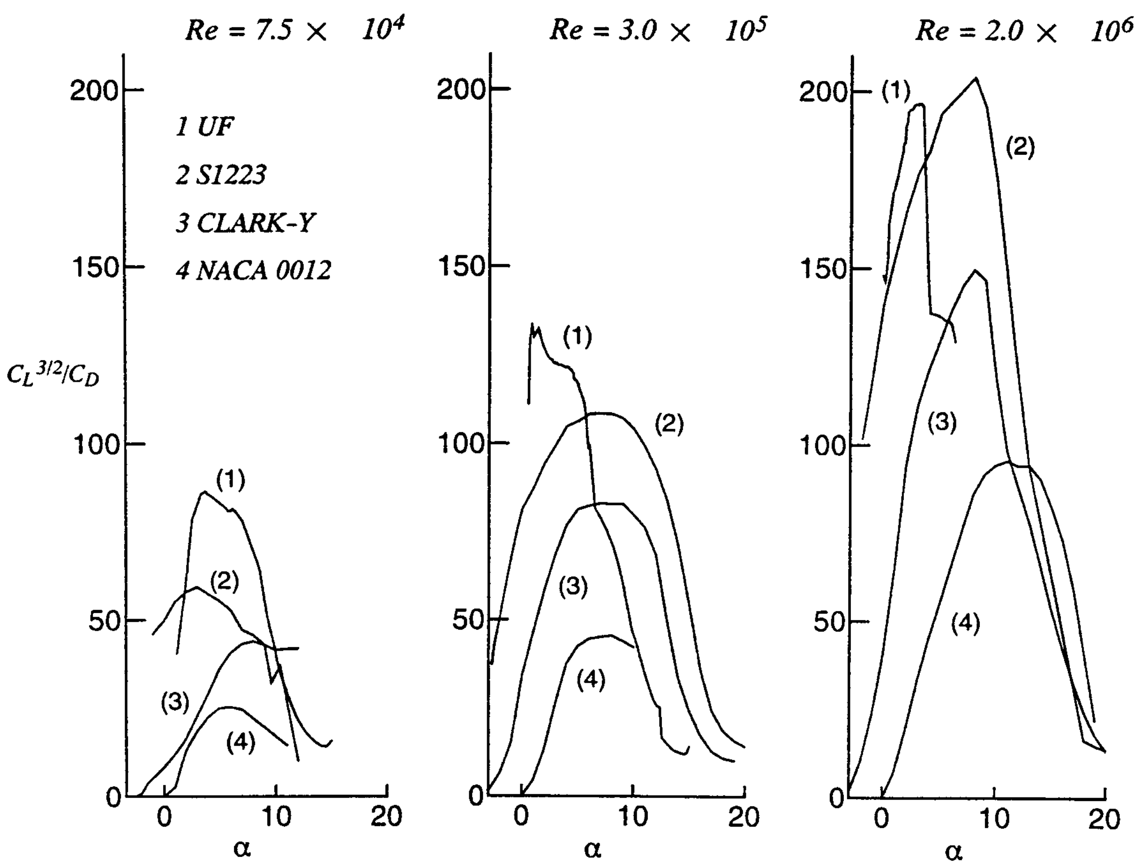


Area	0.06614
Thick.	0.12124
Camber	0.08894
Rad_{LE}	0.04450
$\Delta\theta_{TE}$	67.68°



Area	0.03276
Thick.	0.06000
Camber	0.08877
Rad_{LE}	0.00534
$\Delta\theta_{TE}$	34.17°

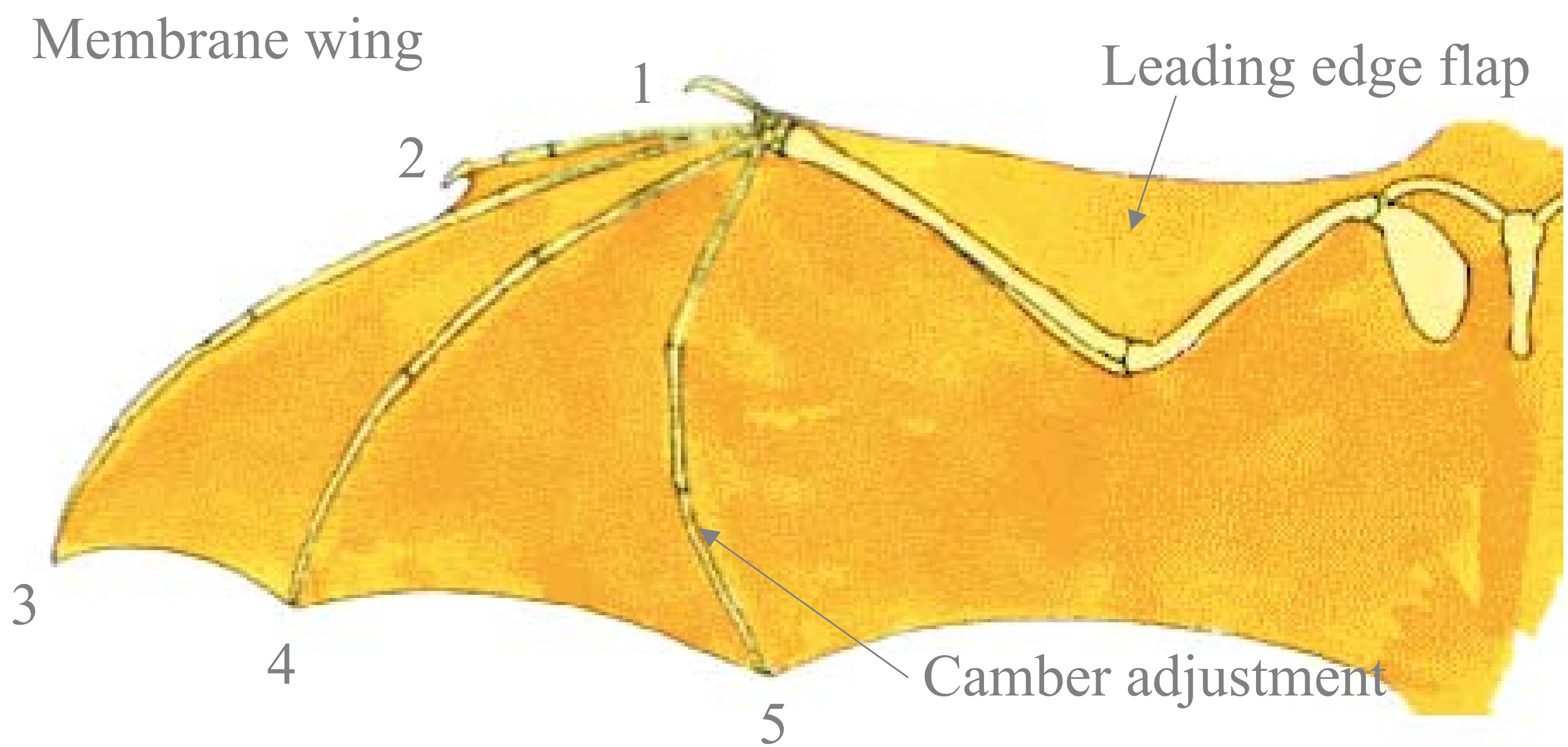
Effects of Re, Airfoil Shape, and AoA on Power Index



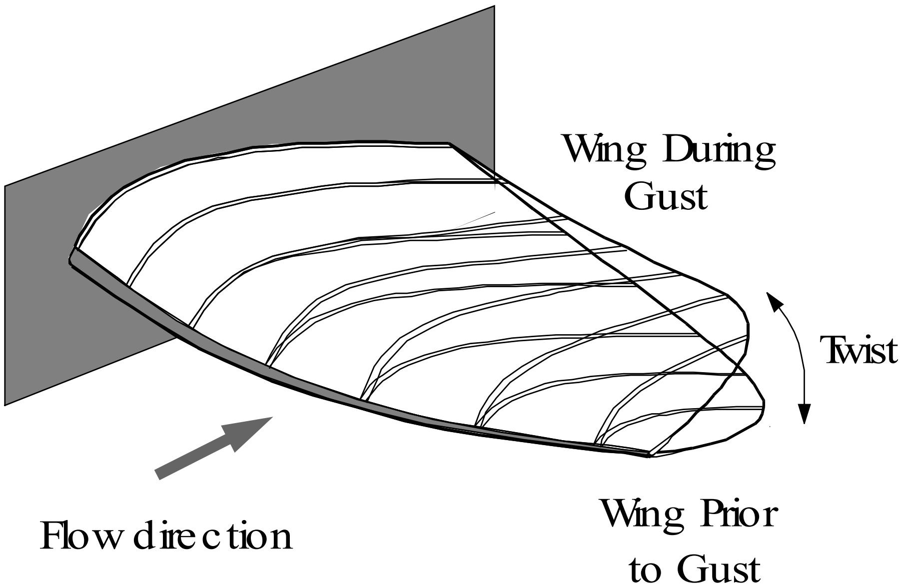
Membrane-Based μAV Concept at U. Florida

- Wingspan: 6 inches
- Length: 5.5 inches
- Weight w/payload, video camera: 2 ounces
- Range: 0.5 mile with off the shelf components
- Endurance: 10 minutes
- Speed Range: 10 – 35 miles/hour
- Propulsion: electric motor
- Batteries: rechargeable Lithium polymer
- Altitude: up to 500 feet AGL

Bat Wing Morphology

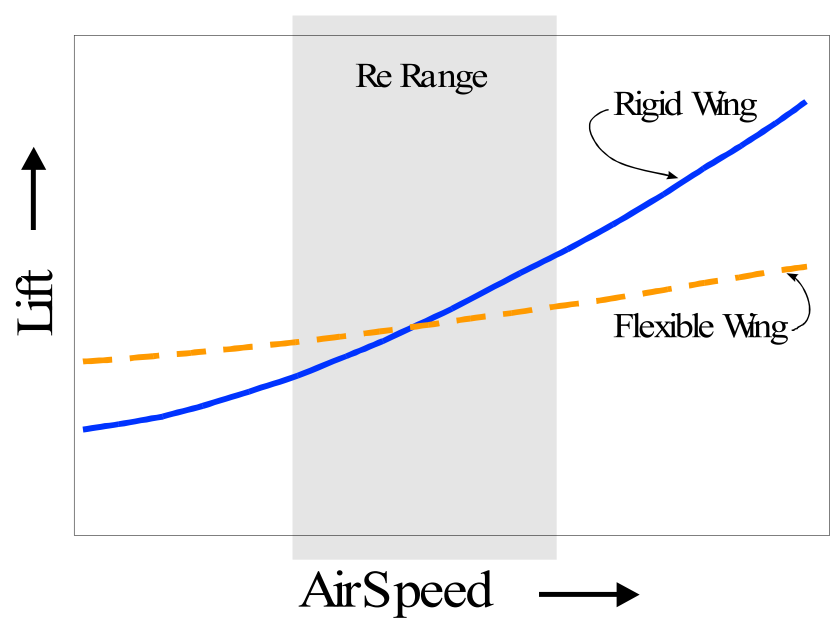


Adaptive Washout for Gust Suppression

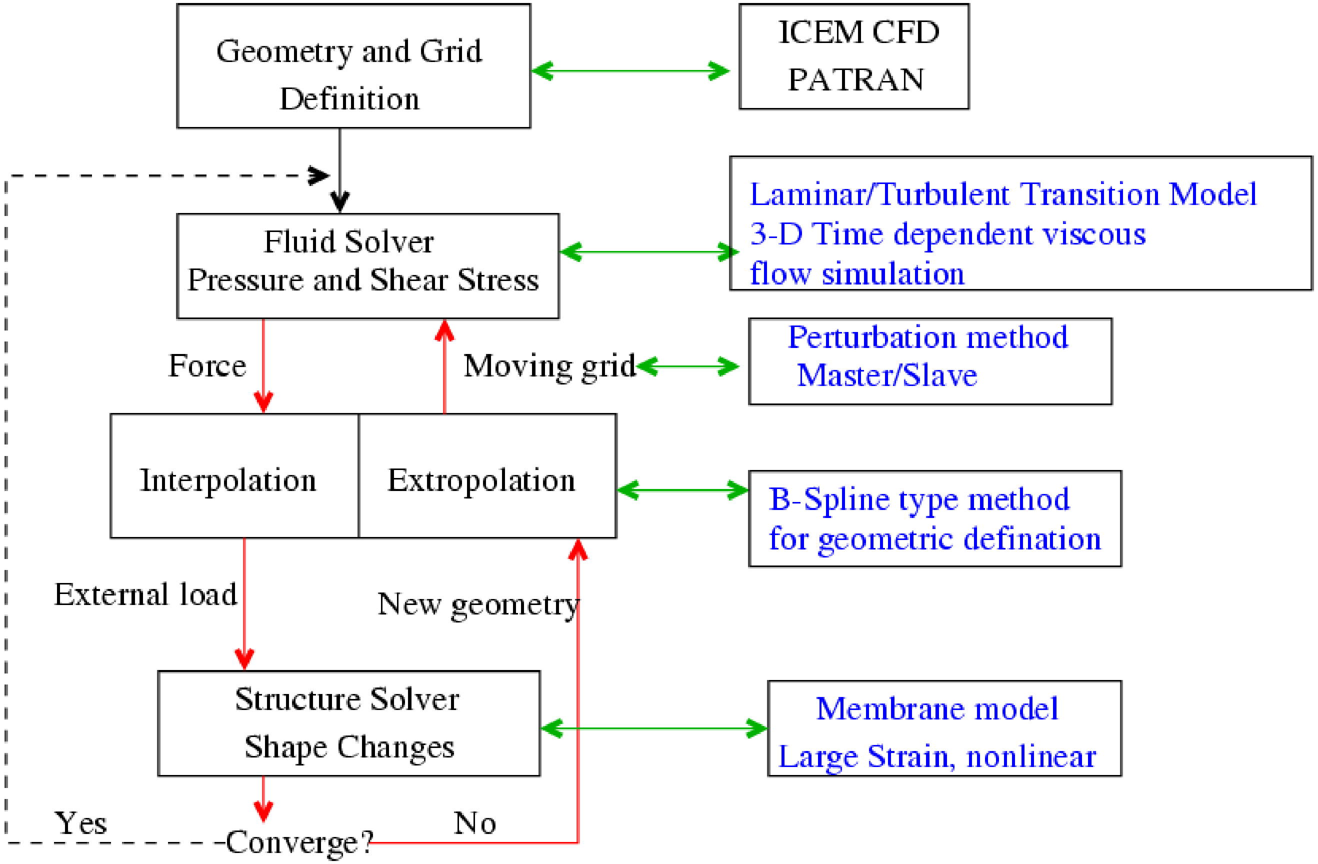


Wing Deformation

Lift Response



Computational Fluid/Structure Interaction

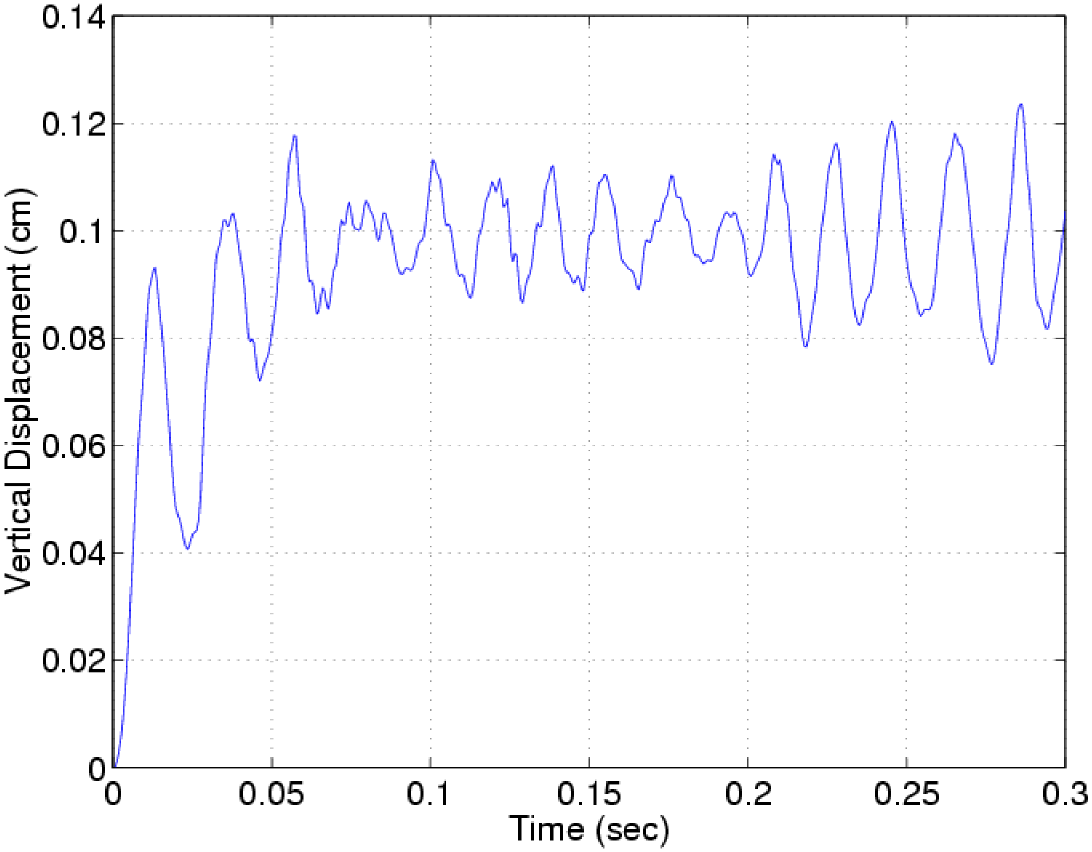


- Fluid solver: Calculate the external force.
- Structure solver: Calculate the shape change.
- Moving boundary: Regenerate the CFD grid
- Interface: Exchange information between fluid and structure solvers.

Approach

- Structure model
  - Dynamic membrane model with finite element.
  - Expect substantial deformation: nonlinearity.
- Fluid flow solver
  - A pressure-based method for 3-D full Navier-Stokes equations
- Grid regeneration
  - 3-stage algebraic TFI-like method.
- Interpolation
  - Thin Plate Spline (TPS) interpolation method

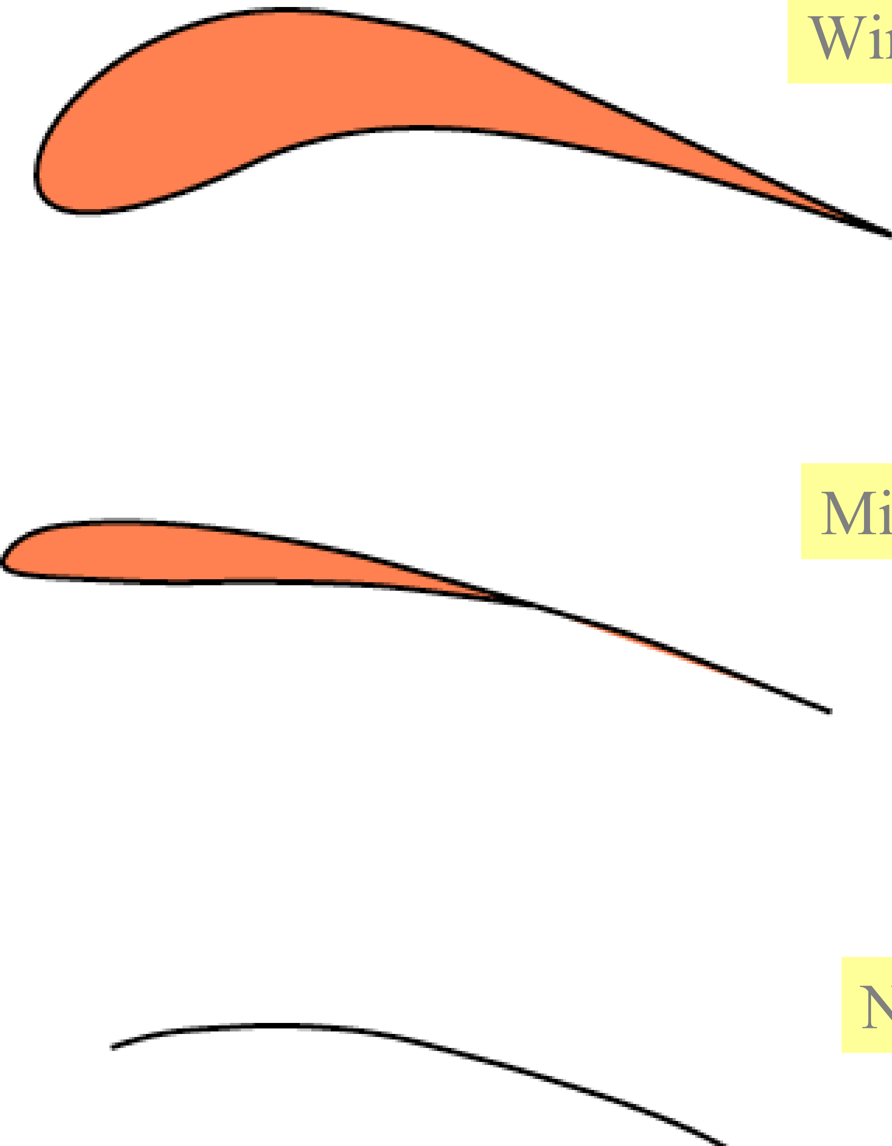
Displacement of trailing edge at mid-span



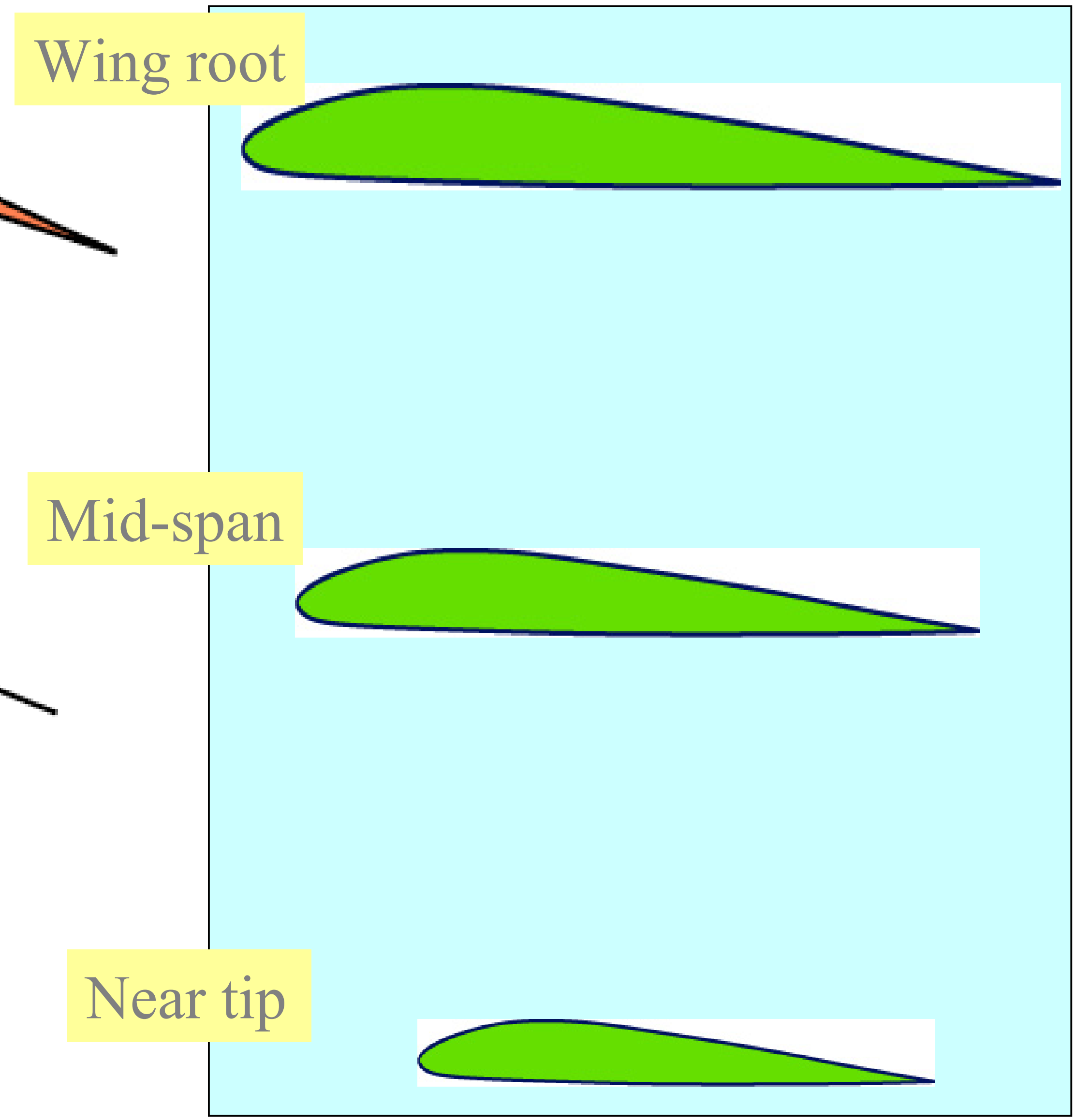
- Steady Free Stream, Re= 9×10^4, AoA=6^o
- Periodic oscillation of the trailing edge point.
- Frequency=67Hz. (Typical wind gust: 1 Hz)
- The effective angle of attack reduced.

Wing Cross Section: Optimization?

Pigeon wing



Conventional Wing



Optimization Scope and Approach

$$\text{Minimize} \quad C_D / C_L$$

Subject to

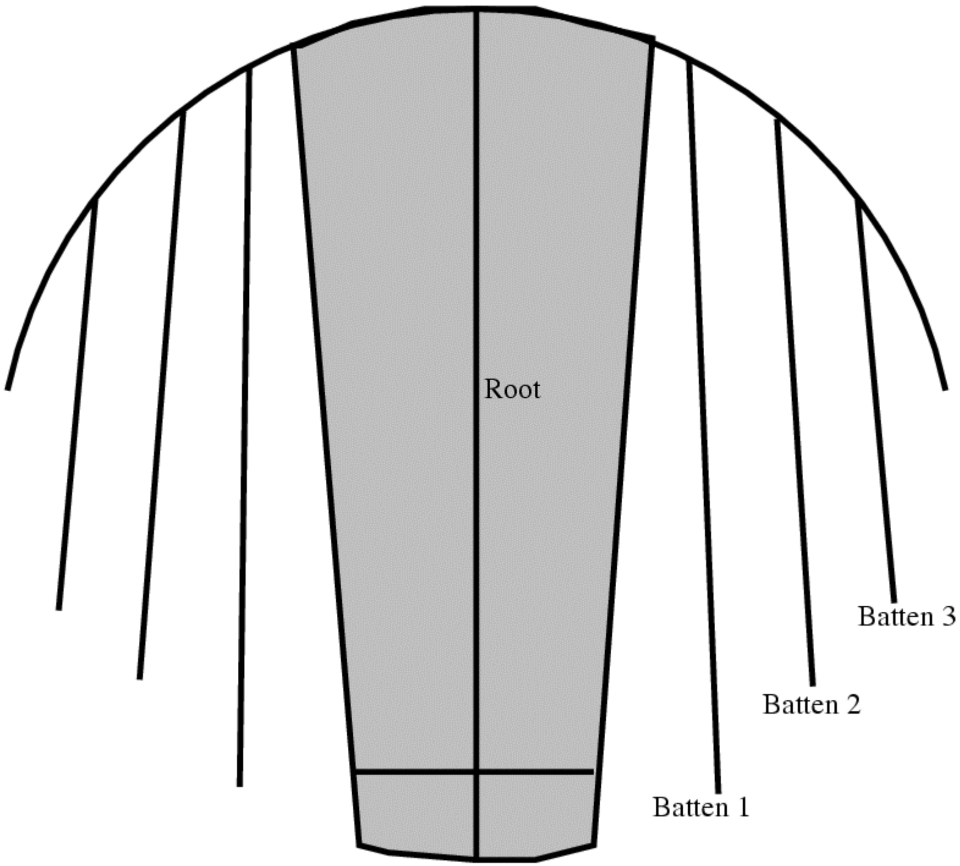
$$1{:}\ C_L \geq C_{L\text{baseline}}$$

$$2{:}\ \text{Convexity constraint:} \quad Y_1 \geq \frac{Y_2 + y_2 - Y_0}{x_2 - x_0}(x_1 - x_0) + y_0 - y_1 + \varepsilon$$

$$3{:}\ Y_i^L \leq Y_i \leq Y_i^U, \qquad i = 1, N$$

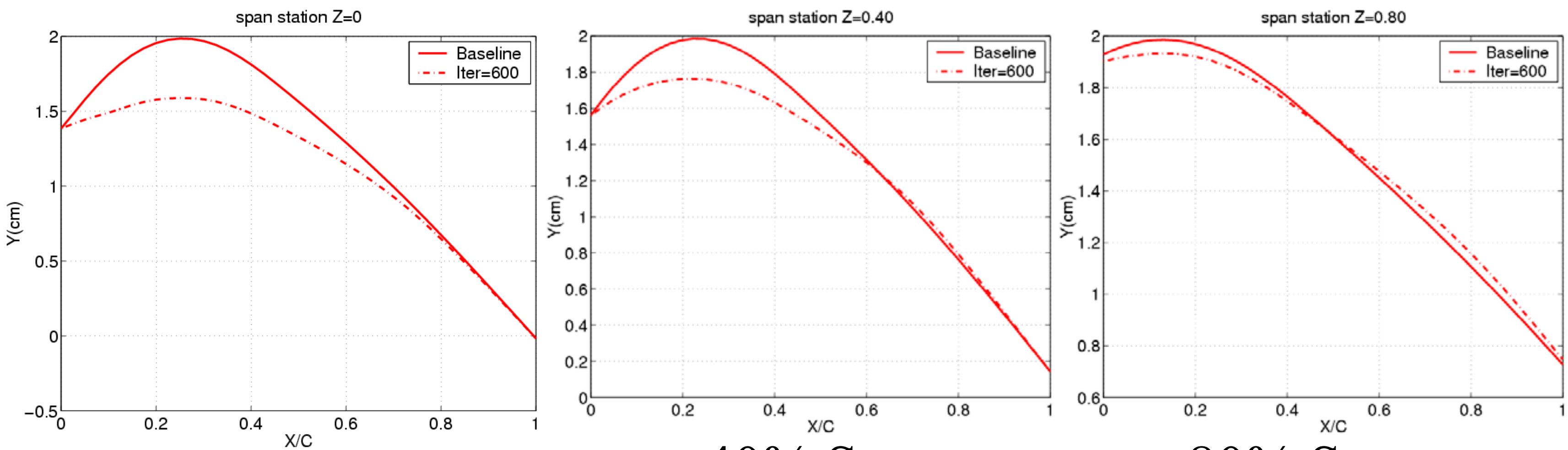
- Maximize L/D; Maintain lift; Keep cross-section convex.
- A direct optimization of membrane wing is time-demanding: Optimize the rigid wing as a surrogate.
- Design Optimization Tools (DOT) used as the optimizer.
- An automatic grid regeneration tool is used to regenerate the CFD grid as each analysis.

Choice of Design Variables



- The baseline design is based results from Xfoil (Drela): which uses a two-equation boundary layer integral formulation & inviscid-BL coupling.
- 6 Design Variables: Three each on battens1 and 2.

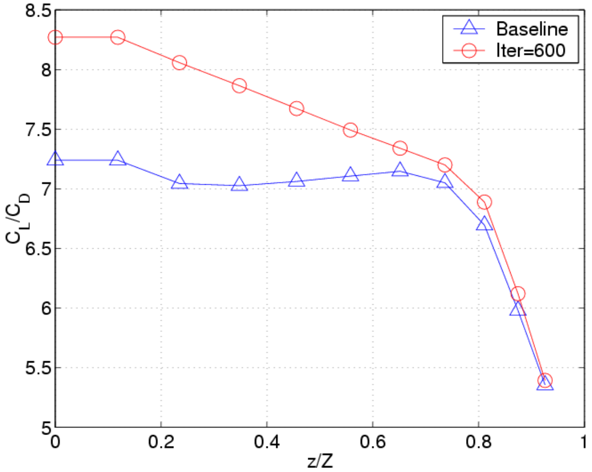
Airfoil Shapes in Spanwise Direction

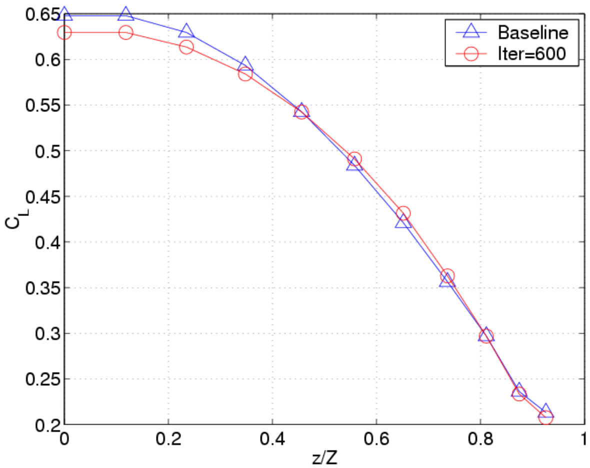


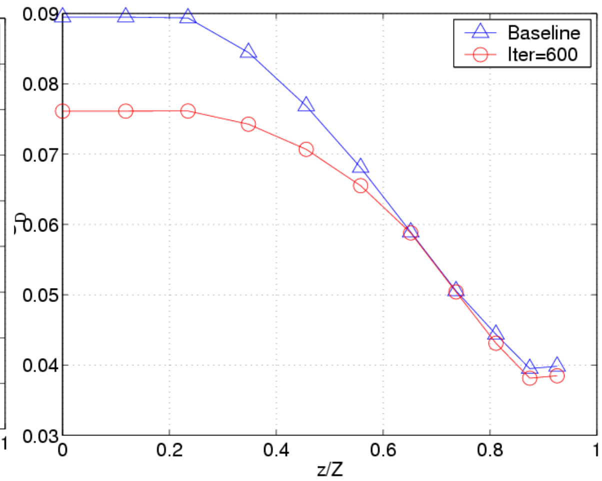
Root　　40% Span　　80% Span

- Compared to the baseline, camber decreases near the root while increases near the tip.
- Overall, the camber is still higher at the root (4.8%) than at the tip (4%).
- In optimization we maintain angle of attack at **6^o**.

Spanwise Aerodynamics at Design Point: Rigid Wing at AoA=6^o

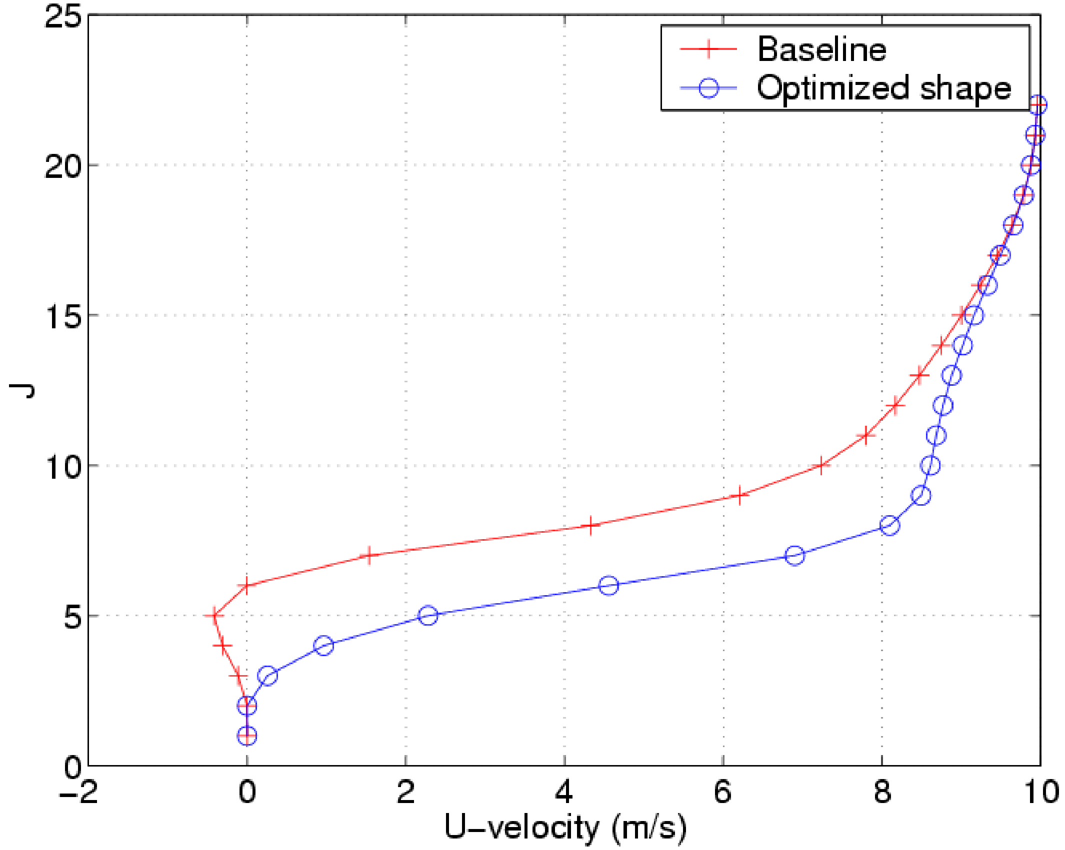






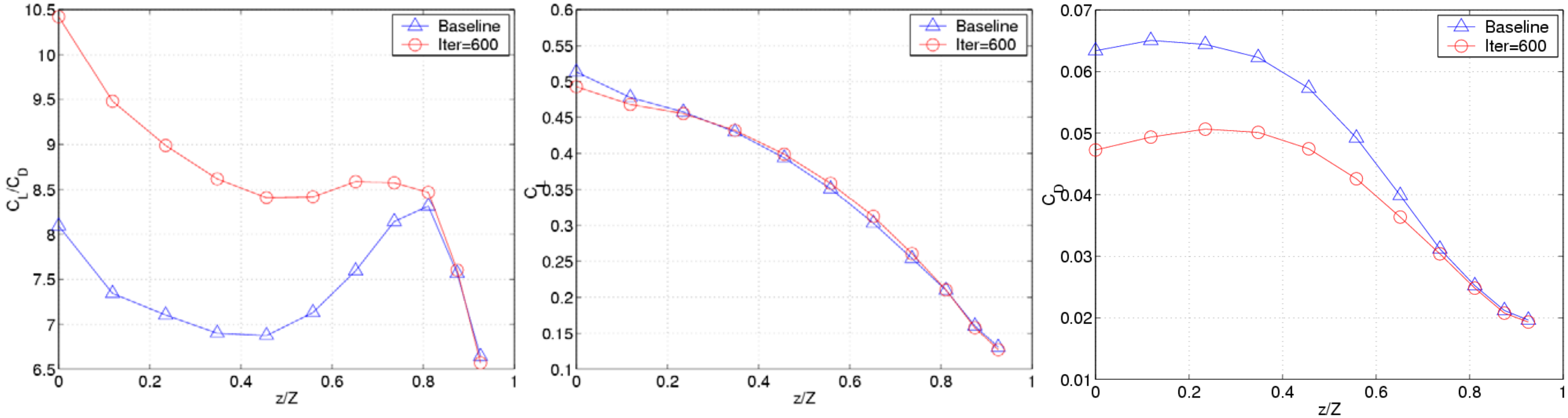
- Optimization can improve L/D.
- The improvement is largely located within 70% of the inner wing.
- Lift coefficient maintains the same even though camber reduces.
- The improvement is largely due to lower form drag.

Velocity Profile Near Root: Rigid Wing



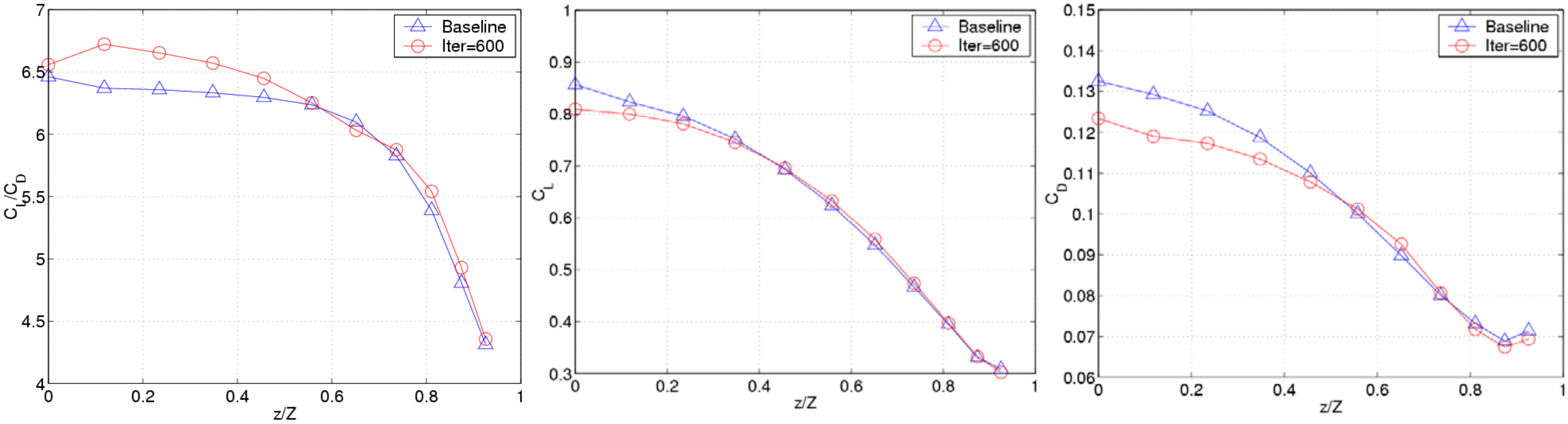
- AoA=6º
- The optimized wing suppresses the flow separation.

Spanwise Aerodynamics at Off-Design Point: Rigid Wing at AoA=3°



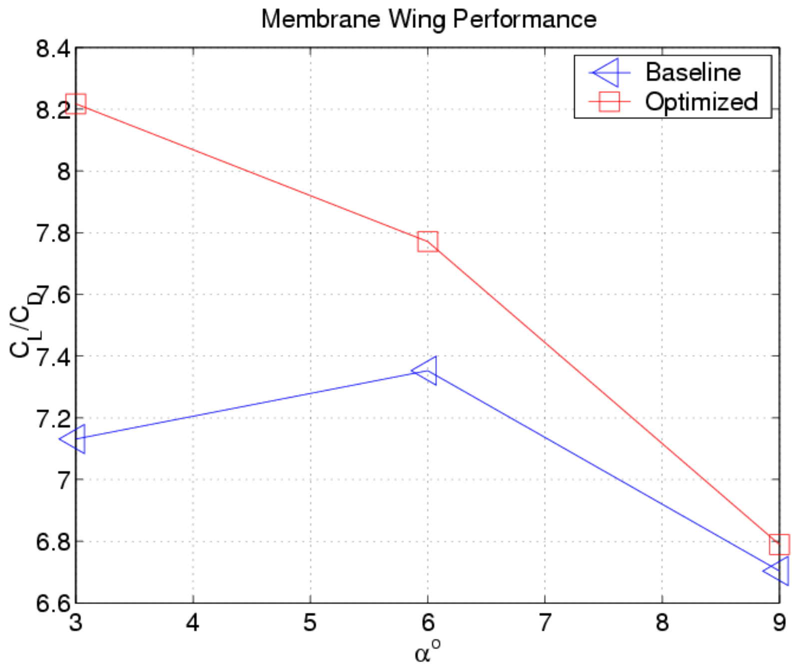
- The improvement is substantial at low AoA, and consistent with the design point, is largely located within 70% of the inner wing.
- Same as the design point, the lift maintains the same even though camber reduces, and the improvement is largely due to lower form drag.

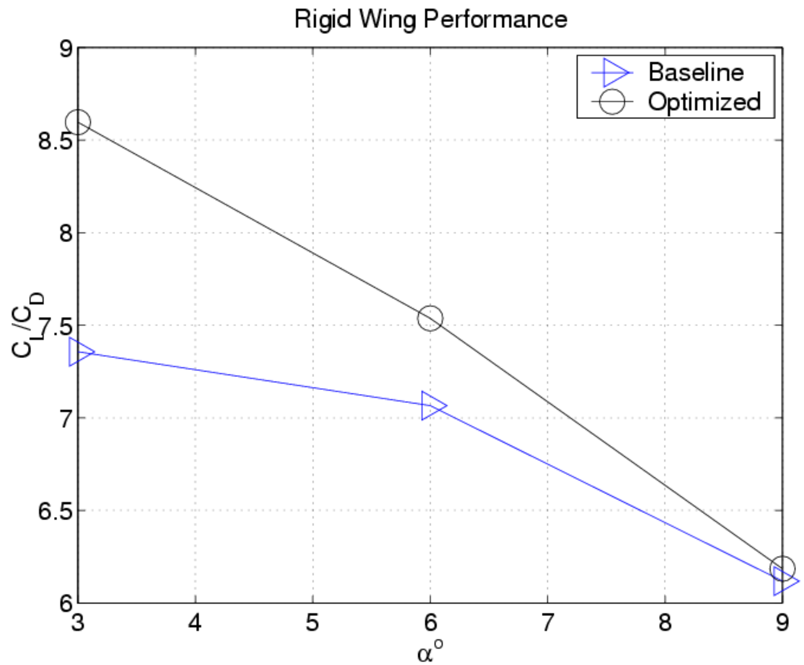
Spanwise Aerodynamics at Off-Design Point: Rigid Wing at AoA=9^o



- At large AoA, improvement with the optimized shape diminishes.

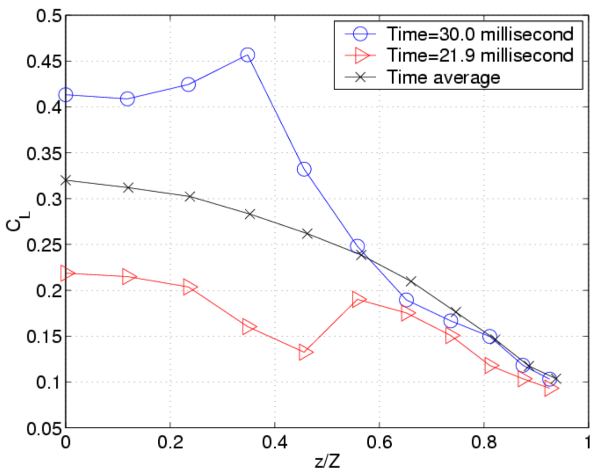
Aerodynamics Between Membrane & Rigid Wings



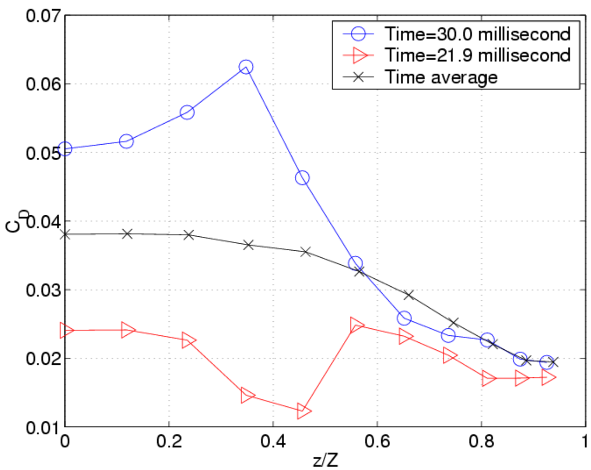


- Optimized shape improves L/D consistently.
- Optimized membrane wing varies less in L/D versus AoA.

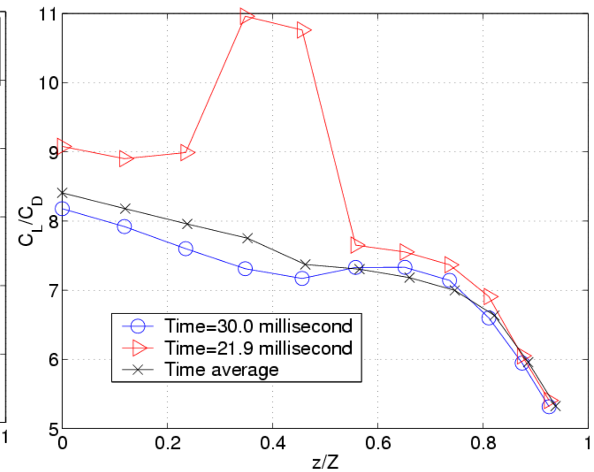
Optimized Membrane Wing at AoA=6^o



Lift



Drag



L/D

- While there seem substantial variations in time, the frequency (about 70Hz) is higher than that environmental fluctuation or vehicle response.

Outstanding Issues/Opportunities

- Optimized materials properties for passive flow control.
- Sensor and simplified aerodynamic model to facilitate autonomous flight control.
- Detailed wind tunnel measurements and numerical simulations to assess the unsteady flight environment.
- Efficient propulsion.